Dynamical energy loss as a tool for QGP Tomography

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Brief overview of Quark Gluon Plasma

- QGP is a **new form of matter**, consisting of deconfined and interacting quarks, antiquarks and gluons.
- QGP is **predicted** by QCD to exist at extremely high energy densities.
One of the most important **goals** of high energy heavy ion physics is to form, observe and understand QGP.

Ultra-Relativistic Heavy Ion Colliders (RHIC and LHC) have been made at BNL and CERN.
Scheme of relativistic heavy ion collisions

Simulation “VNI” (Geiger, Longacre, Srivastava)

Heavy ion acceleration
Collision
Quark-gluon plasma
Hadron Gas

To study the properties of QCD matter created at URHIC we need good probes

High energy particles (E > 10 GeV) are widely recognized as the excellent probes of QGP.
Why are high energy particles good probes?

High energy particles:

• Are produced only during the early stage of QCD matter.
• Significantly interact with the QCD medium
• Perturbative calculations are possible
Jet suppression is considered to be an excellent probe of QCD matter.

What is suppression?

Jet suppression

Initial momentum distribution

$\frac{d\sigma}{d^2p_\perp} (\text{mb/GeV}^2)$

$p_\perp [\text{GeV}]$
Jet suppression is considered to be an excellent probe of QCD matter.

What is suppression?

Suppression = \frac{\text{Final momentum distribution}}{\text{Initial momentum distribution}}
1) Initial momentum distributions for partons
2) Parton energy loss
3) Fragmentation functions of partons into hadrons
4) Decay of heavy mesons to single $e^-$ and $J/\psi$. 
Energy loss in QGP
Radiative energy loss

Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:

Collisional energy loss

Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:
Radiative energy loss
Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:

\[ \text{0th order} \]
\[ \text{1st order} \]

Collisional energy loss
Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:

\[ \text{0th order} \]

Considered to be negligible compared to radiative!
Radiative energy loss is not able to explain the single electron data as long as realistic parameter values are taken into account!


Radiative energy loss predictions with $dN_g/dy=1000$

Disagreement!
Does the radiative energy loss control the energy loss in QGP?

Is collisional energy loss also important?
Collisional energy loss in a finite size QCD medium

Consider a medium of size $L$ in thermal equilibrium at temperature $T$.

The main order collisional energy loss is determined from:

\[ \begin{align*}
D^{\mu\nu}(\omega, \vec{q}) &= - P^{\mu\nu} \Delta_T(\omega, \vec{q}) - Q^{\mu\nu} \Delta_L(\omega, \vec{q}) \\
\end{align*} \]

Collisional v.s. medium induced radiative energy loss

Collisional and radiative energy losses are comparable!
Non-zero collisional energy loss - a fundamental problem

With such approximation, collisional energy loss has to be exactly equal to zero!

Static QCD medium approximation (modeled by Yukawa potential).

Introducing collisional energy loss is necessary, but inconsistent with static approximation!

However, collisional and radiative energy losses are shown to be comparable.

Static medium approximation should not be used in radiative energy loss calculations!

Dynamical QCD medium effects have to be included!
Our goal

We want to compute both radiative and collisional energy loss in dynamical medium of thermally distributed massless quarks and gluons.

Why?

- To address the applicability of static approximation in radiative energy loss computations.
- To compute collisional and radiative energy losses within a consistent theoretical framework.

Radiative energy loss in a dynamical medium

We compute the medium induced radiative energy loss for a heavy quark to first (lowest) order in number of scattering centers.

To compute this process, we consider the radiation of one gluon induced by one collisional interaction with the medium.

We consider a medium of finite size $L$, and assume that the collisional interaction has to occur inside the medium.

The calculations were performed by using two Hard-Thermal Loop approach.
For radiated gluon, cut 1-HTL gluon propagator can be simplified to

\[ D_{\mu\nu}^> (k) \approx -2\pi \frac{P_{\mu\nu}(k)}{2\omega} \delta(k_0 - \omega) \]

\[ \omega \approx \sqrt{k^2 + m_g^2}; \quad m_g \approx \mu/\sqrt{2} \]

For exchanged gluon, cut 1-HTL gluon propagator cannot be simplified, since both transverse (magnetic) and longitudinal (electric) contributions will prove to be important.

\[ D_{\mu\nu}^> (q) = \theta(1 - \frac{q_0^2}{q^2})(1 + f(q_0)) 2 \text{Im} \left( \frac{P_{\mu\nu}(q)}{q^2 - \Pi_T(q)} + \frac{Q_{\mu\nu}(q)}{q^2 - \Pi_L(q)} \right) \]

1-HTL gluon propagator:

\[ iD_{\mu\nu}^{\mu\nu}(l) = \frac{P_{\mu\nu}(l)}{l^2 - \Pi_T(l)} + \frac{Q_{\mu\nu}(l)}{l^2 - \Pi_L(l)} \]

Cut 1-HTL gluon propagator:

\[ D_{\mu\nu}^> (l) = -(1 + f(l_0))(P_{\mu\nu}(l)\rho_T(l) + Q_{\mu\nu}(l)\rho_L(l)), \]

\[ \rho_{L,T}(l) = 2\pi \delta(l^2 - \Pi_{T,L}(l)) - 2 \text{Im} \left( \frac{1}{l^2 - \Pi_{T,L}(l)} \right) \theta(1 - \frac{l_0^2}{l^2}) \]
More than one cut of a Feynman diagram can contribute to the energy loss in finite size dynamical QCD medium:

These terms interfere with each other, leading to the nonlinear dependence of the jet energy loss.

We calculated all the relevant diagrams that contribute to this energy loss.

Each individual diagram is infrared divergent, due to the absence of magnetic screening!

The divergence is naturally regulated when all the diagrams are taken into account. So, all 24 diagrams have to be included to obtain sensible result.

\[
\frac{\Delta E_{\text{dyn}}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\text{dyn}}} \int dx \frac{d^2 k}{\pi} \frac{d^2 q}{\pi} \frac{\mu^2}{q^2 (q^2 + \mu^2)} \left( 1 - \frac{\sin \left( \frac{(k+q)^2 + \chi}{x E^+} \right)}{\frac{(k+q)^2 + \chi}{x E^+}} \right)
\times \frac{(k+q)}{(k+q)^2 + \chi} \left( \frac{(k+q)}{(k+q)^2 + \chi} - \frac{k}{k^2 + \chi} \right),
\]

Finite magnetic mass

The dynamical energy loss formalism is based on HTL perturbative QCD, which requires zero magnetic mass.

However, different non-perturbative approaches show a non-zero magnetic mass at RHIC and LHC.

Can magnetic mass be consistently included in the dynamical energy loss calculations?
Generalization of radiative jet energy loss to finite magnetic mass

\[ \frac{\Delta E_{\text{dyn}}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\text{dyn}}} \int dx \frac{d^2 k}{\pi} \frac{d^2 q}{\pi} \frac{\mu^2}{q^2(q^2 + \mu^2)} \times 2 \frac{(k+q)}{(k+q)^2 + \chi} \left( \frac{1 - \frac{k}{k^2 + \chi}}{\frac{1}{xE^+} + \frac{\sin \left( \frac{kq}{xE^+} \right)}{xE^+}} \right) \]

From our analysis, only this part gets modified.

Finite magnetic mass: \( \frac{\mu_E^2 - \mu_M^2}{(q^2 + \mu_E^2)(q^2 + \mu_M^2)} \), where \( 0.4 \leq \frac{\mu_M}{\mu_E} \leq 0.6 \).

Computing both collisional and radiative energy loss, in a finite size QCD medium, composed of dynamical scatterers.

Finite magnetic mass effects
M. D. and M. Djordjevic, PLB 709:229 (2012)

Includes running coupling

State of the art energy loss formalism in a dynamical finite size QCD medium.

Numerical importance of different effects addressed in
Numerical procedure

• **Light flavor production** Z.B. Kang, I. Vitev, H. Xing, PLB 718:482 (2012)
• **Heavy flavor production** M. Cacciari et al., JHEP 1210, 137 (2012)
• **Multi-gluon fluctuations**
• **DSS and KKP fragmentation for light flavor**
• **BCFY and KLP fragmentation for heavy flavor**
• **Decays of heavy mesons to single electron and J/ψ according to**
  M. Cacciari et al., JHEP 1210, 137 (2012)
• **Temperature T=304 MeV for LHC and T=221 MeV for RHIC.**
Comparison with the experimental data
• **Provide joint predictions across diverse probes**
  charged hadrons, pions, kaons, D mesons,
  non-photonic single electrons, non-prompt J/ψ
  M. D. and M. Djordjevic, PLB 734, 286 (2014)

• **Concentrate on all centrality regions**
  M. D., M. Djordjevic and B. Blagojevic, PLB 737 298 (2014)

• **Provide predictions for the upcoming data**

• **All predictions generated**
  ➢ By the same formalism
  ➢ With the same numerical procedure
  ➢ No free parameters in model testing
Comparison with LHC data (central collision)

M. D. and M. Djordjevic, PLB 734, 286 (2014)

Very good agreement with diverse probes!
Comparison with RHIC data (central collisions)

Very good agreement!

M.D. and M. Djordjevic, PRC 90, 034910 (2014)
$R_{AA}$ vs. $N_{\text{part}}$ for RHIC and LHC

Excellent agreement for both RHIC and LHC and for the whole set of probes!

M. D., M. Djordjevic and B. Blagojevic, PLB 737 298 (2014)
5.02 TeV Pb+Pb at LHC


The same suppression as at 2.76 TeV for all types of probes!

Confirmed by experimental data in July 2016!
Summary

Dynamical energy loss formalism.

Tested on angular averaged $R_{AA}$ data.

Largely not sensitive to the medium evolution.

Good agreement for wide range of probes, centralities and beam energies.

Can explain puzzling data.

Clear predictions for future experiments.

The dynamical energy loss formalism can well explain the jet-medium interactions in QGP.